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Critical Activities for Mold Development in Wood Product Manufacturing

I. Introduction

Mold in wooden furniture is a frequently overlooked yet serious issue. Its growth not only causes visible damage and quality deterioration but can also, in more severe cases, lead to the breakdown of internal structural materials, thereby shortening the product's lifespan (Wu et al., 2022). Mold development is influenced by multiple environmental factors and conditions, including high relative humidity caused by humid climates, fluctuations in indoor temperature, and surface condensation. These conditions can create favorable environments for spore germination and hyphal growth (Silveira et al., 2019). Beyond external environmental factors, the furniture manufacturing process itself also contributes to mold susceptibility. Therefore, a comprehensive understanding and effective management of mold problems in wooden furniture require consideration of the potential impacts of each stage of the production process (Gradeci et al., 2017).

This article thus aims to systematically review and examine the mold-related risk factors within the wooden furniture manufacturing process and to propose potential improvement strategies that support product quality, durability, and environmentally sustainable development.

II. Literature Review

Tracing back to the initial stages of mold development in wooden furniture, mold sources can be classified into three main categories. The first is primary contamination, where wood may already carry fungal spores or endophytes during the forest stage, which can become active during felling, transportation, or temporary storage. The second is factory environment contamination, where airborne microorganisms, equipment dust, and worker clothing in the factory can all serve as spore sources, causing secondary contamination. Finally, there are regional variations in wood characteristics, where different tree species and origin climate conditions (such as temperature, humidity, and biological communities) affect mold community structure and species composition. In summary, these sources accumulate after wood enters the factory, forming the foundation of potential fungal

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sources and making subsequent drying, bonding, and coating stages potential critical points for mold reactivation and proliferation (Szwajkowska-Michałek et al., 2020; Johansson et al., 2017; Poohphajai et al., 2023).

(i) Wood Moisture Content and Acceptance Standards

As an organic material, wood's susceptibility to mold growth is significantly influenced by temperature, with optimal growth temperatures varying slightly among different fungal species. Common mold species on wood generally grow between 10°C and 40°C, with most thriving between 20°C and 30°C, including *Aspergillus niger*, *Penicillium citrinum*, and *Aureobasidium pullulans*. Under extreme climatic conditions, growth may be inhibited (Kopecký et al., 2023). Additionally, moisture is one of the most important abiotic factors affecting mold growth, providing ideal conditions for fungal development (Kuka et al., 2022). Research indicates that when wood moisture content reaches 20% or above, the risk of mold growth significantly increases, highlighting the critical importance of wood moisture management (Viitanen & Ritschkoff, 1991; Zabel & Morrell, 2020). In practical factory operations, establishing acceptance standards for wood is of greater practical significance. Generally, factories set raw material moisture content controls at 8-12% to meet furniture manufacturing requirements. This is primarily because multiple studies indicate that wood determines mold risk critically through relative humidity and equilibrium moisture content (EMC). If moisture content exceeds target values, especially in environments with high relative humidity or localized dampness, the risk of mold germination increases significantly. According to the literature, 20% is commonly used as a safety margin and lower threshold for mold occurrence (Viitanen & Ritschkoff, 1991; Zabel & Morrell, 2020).

Although long-term statistical data on mold development timing in wooden furniture is currently lacking, the VTT Mould Growth Model developed by Viitanen allows quantification of risk variations using the Mould Index (M), where M ≥ 3 represents visible growth. The model can predict the time required to reach this threshold based on temperature and relative humidity. For sensitive wood species, simulation results show that under conditions of approximately 80% relative humidity and

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25°C temperature, visible growth may occur within roughly two weeks, though actual timing varies depending on material type and humidity fluctuations (Viitanen & Ojanen, 2007).

(ii) Wood Selection and Storage Environmental Conditions

Firstly, in wooden furniture manufacturing, wood selection and storage-drying conditions are critical factors affecting mold formation. Different tree species possess varying natural durability due to differences in chemical composition and structure, which influences their resistance to mold (Hill, 2006). For example, hardwoods are easily invaded by mold in high-humidity environments, while some softwoods contain natural antimicrobial compounds—such as phenolic compounds (taxifolin, flavonoids) in the heartwood of certain coniferous species—that can effectively inhibit fungal invasion (Curnel et al., 2008; Gierlinger et al., 2003). Conversely, broadleaf species (such as linden or poplar) lack such compounds and therefore have lower resistance to mold; when stored in humid environments, they become even more susceptible to mold proliferation (Zabel & Morrell, 2020). Furthermore, the climate and resident microbiota of the raw wood's origin determine the initial contamination pressure when materials enter the factory. Wood from tropical and subtropical regions, having been exposed to high temperature, high humidity, and abundant spore sources in their native environments, often already harbors moisture-loving mold spores (*Aspergillus*, *Trichoderma*) during felling and transportation. If improperly handled upon factory entry, these spores can rapidly activate and develop initial mycelia, becoming early-stage mold germination sources in the manufacturing process (Hu et al., 2021).

However, at the factory level, since raw material tree species selection is often limited, the more practical approach lies in strict control of drying and storage conditions. Wood typically requires natural air-drying or artificial drying to ensure it meets standard ranges for furniture manufacturing and extends storage life (Glass and Zelinka). However, if the drying process is unevenly controlled, moisture content differences between the wood's interior and exterior can cause internal stress (drying stress), potentially resulting in "dry surface, moist interior" conditions that provide locally suitable

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environments for mold growth (Forest Products Laboratory, 2021; Yin & Liu, 2021).

Additionally, storage conditions significantly affect mold risk. Research shows that if wood is not completely dried and remains stacked for extended periods, internal moisture content continues to rise, providing suitable environments for mold spore growth (Viitanen & Ritschkoff et al., 1991). Simultaneously, when storage space relative humidity remains above 70% for extended periods, even if wood meets standards upon acceptance, it may still absorb atmospheric moisture and form condensation, creating localized damp areas that promote mold growth (Johansson et al., 2012). Therefore, drying uniformity, ventilation design, and relative humidity control are all core elements in reducing mold risk during furniture manufacturing processes.

(iii) Cross-contamination from Processing Tools

During wood product manufacturing, the processing stage represents a critical turning point for mold prevention risk. Tools used in wood processing—such as cutting machines, planers, sanders, and drills—if not regularly cleaned or disinfected, can easily become transmission vectors for mold spores, leading to cross-contamination risks. Research has shown that air and equipment surfaces in woodworking factories commonly harbor spores from genera such as *Aspergillus* and *Penicillium*, which can transfer to semi-finished wood products through airflow, contact, or electrostatic attachment (Dias et al., 2022).

Furthermore, wood chips and dust generated during processing, if not promptly handled or properly cleaned, settle and persist on tool surfaces or equipment. Due to their high surface area and moisture content, wood chips easily become microenvironments for spore attachment and reproduction. When these contaminants subsequently contact insufficiently dried or untreated wood, they can lead to cross-contamination and early mold colonization (Pędzik et al., 2021; Szwajkowska-Michałek et al., 2020). Spores introduced by equipment and dust readily accumulate in furniture edges, end-grain areas, and joints—microregions with high water absorption that form localized moisture spots first when environmental humidity rises, prompting dormant spores to re-

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germinate and initiate mycelial growth (Kuka et al., 2022; Thickett et al., 2014).

Therefore, processing tools function not only as production equipment in furniture manufacturing but also as significant mold risk sources that cannot be overlooked. Without effective management—including regular equipment cleaning and disinfection, timely removal of wood chips and dust, maintaining ventilation and dryness in processing areas, and establishing tool maintenance and operation protocols—the potential risk of finished products becoming contaminated during early processing stages will substantially increase.

(iv) Adhesives

The use of adhesives (resins) has significant impact on product mold resistance. Traditionally, urea-formaldehyde resin (UF), polyvinyl alcohol (PVA), and phenol-formaldehyde resin (PF) are frequently selected due to their lower cost, fast curing reaction speed, good processing convenience, and excellent wood compatibility—comprehensive factors making them widely applied in fiberboard and furniture industries. However, their differences in hygroscopicity, durability, and antimicrobial properties represent important variables affecting mold risk (Frihart, 2005; Garzón-Barrero et al., 2016; Morsi et al., 2024; Pizzi & Mittal, 2005).

Regarding adhesive water absorption differences, specimens using PF adhesive showed approximately 69% water absorption and about 20% thickness swelling after 24-hour water immersion, while specimens using UF adhesive exhibited nearly double the water absorption and swelling of PF adhesive. This demonstrates that UF adhesive more readily absorbs water and swells, and more easily loses stability under moist conditions (Zeleniuc et al., 2019).

Beyond water absorption, adhesive durability and antimicrobial properties are also key factors affecting wood product mold resistance performance. Different adhesive types' variations in chemical structure and crosslink density determine their resistance to humidity, temperature, and microbial degradation. For example, due to its structure containing free formaldehyde and hydrophilic groups, literature indicates UF adhesive is more susceptible to mold invasion in high-humidity environments and requires additional preservatives or modification to improve mold resistance

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(Dunky, 1998; Park and Jeong, 2011; Vidholdová et al., 2024). Meanwhile, PVA adhesive's molecular structure contains abundant hydroxyl groups (--OH), and its high hydrophilicity causes it to more readily absorb water and swell in high-humidity environments, loosening internal material structure while simultaneously reducing adhesive layer mechanical strength and durability (Chiellini et al., 2003).

As traditional adhesives' mold resistance effectiveness receives attention, recent years have seen numerous studies propose multiple improvement directions. First, structural stability can be improved by increasing crosslinking degree, such as adding glutaraldehyde (GA) or nanocellulose to UF adhesive to enhance crosslinking and significantly improve tolerance while reducing performance degradation (Mamiński et al., 2007). On the other hand, considering environmental friendliness, natural polymer adhesives (such as starch and lignin) have received widespread attention, but due to their higher organic content, they can easily become potential nutrients for mold and thus require combination with antimicrobial modification to ensure long-term stability (Chen et al., 2021; Doherty et al., 2011; Maulana et al., 2022). In summary, adhesive technology is developing toward "low volatility, strong durability, and environmental friendliness," with "composite strategies" becoming current research focuses, balancing performance while reducing environmental impact (Solt et al., 2019).

(v) Coatings and Chemical Treatments

During wood furniture manufacturing and use, coatings and chemical treatments have long been regarded as critical mold prevention measures. Coatings can form barriers on wood surfaces, reducing penetration of external moisture and nutrients, and inhibit mold attachment and germination through added antimicrobial agents or natural extracts. Chemical treatments can penetrate deep into wood structure layers, providing long-lasting antibacterial and anti-decay protection, particularly for export, outdoor, or long-term durability furniture products. While these measures can effectively slow and delay mold risk, their effectiveness is not permanent—protective efficacy gradually declines over time with environmental and material characteristics. According to relevant research, their protective effects and limitations can be further

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explored from the following perspectives:

(1) Protective Effects of Coatings

Wood coating protective effects primarily derive from two aspects. First, physical barriers formed on surfaces can reduce entry of external moisture and soluble substances, decreasing conditions required for mold growth (Rowell, 2012). Second, antimicrobial compounds commonly added to coatings, such as IPBC (iodopropynyl butylcarbamate) and OIT (isothiazolinone), can directly inhibit mold growth. Recent years have also seen research attempting to replace chemical mold inhibitors with natural components such as tannic acid and plant essential oils, demonstrating environmentally friendly and potentially effective antimold properties (Broda, 2020; Freeman & McIntyre, 2008; Schultz et al., 2007). In wood tests with tannic acid component surface modification, results showed antimold effectiveness improved 87.5% compared to controls, confirming tannic acid as a natural component for enhancing coating mold resistance (Wang et al., 2022). After applying natural essential oils to wood sample surface treatments, significant inhibitory effects were demonstrated against common wood molds including *Aspergillus niger*, *Penicillium citrinum*, and *Trichoderma viride*(Hu et al., 2021). This indicates that natural essential oils can serve not only as active mold inhibitors in surface treatments but also be formulated into coatings for wooden furniture or building materials, effectively inhibiting common wood mold growth.

(2) Coating Performance Degradation

Although coatings can effectively provide protection initially, their effectiveness gradually decreases over time. UV radiation, rain washing, and temperature changes all cause coating cracking or peeling, weakening barrier effectiveness (Evans et al., 1992; Williams, 2005). Additionally, some coatings initially inhibit mold due to alkalinity, but as materials age and environmental effects occur (such as humidity fluctuations and carbon dioxide adsorption), surface pH gradually approaches neutrality, weakening inhibitory effects and returning to chemical environments optimal for mold growth (Filali et al., 2024; Mutschlechner et al., 2024; Wheeler et al., 1991).

(3) Chemical Treatment Applications

Wood chemical treatments can

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provide deep and lasting protective effects. Past traditional chemicals such as chromated copper arsenate (CCA), alkaline copper quaternary (ACQ), and copper azole (CuAz) as preservatives could significantly inhibit decay and mold but raised concerns due to toxicity and environmental risks (Hingston et al., 2001; Lebow, 2010; Schultz & Nicholas, 2002). Therefore, recent research has gradually shifted toward low-toxicity, environmentally friendly alternatives such as polyphenols and tannic acid—natural-source substances proven to possess certain mold prevention potential (González-Laredo et al., 2015; Kartal et al., 2009).

III. Conclusion

Through the above analysis, it is evident that mold risk in wood product manufacturing is not caused by a single factor but rather results from the combined effects of multiple factors including raw material moisture content, drying uniformity, storage methods, cross-contamination during processing stages, and integrity of surface protective layers. Among these, control of wood moisture content and equilibrium moisture content represents the core of overall risk management. After drying, if moisture content rebounds due to improper stacking methods or environmental humidity fluctuations, localized moisture spots easily form, becoming starting points for rapid mold activation. Simultaneously, if coatings or surface protective layers are unevenly distributed, creating weak areas at edges or end faces, water vapor can more easily penetrate and concentrate, amplifying the impact of these localized moisture spots and accelerating mold growth and surface degradation.

Therefore, wood product manufacturers can prioritize moisture content monitoring, drying and storage management, coating uniformity inspection, and equipment and environmental hygiene to establish more complete mold prevention control systems. These manufacturing process management-centered measures help reduce risks of early mold development, discoloration, and structural degradation while improving product stability and durability during storage, transportation, and final use scenarios.

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